Infrared Counterpart of the Gravitational Lens 1938+66.6

James E. Rhoads, Sangeeta Malhotra, & Tomislav Kundić

Princeton University Observatory, Peyton Hall, Princeton, NJ 08544

rhoads@astro.princeton.edu,san@astro.princeton.edu, tomislav@astro.princeton.edu

ABSTRACT

We report the detection of a very red source coincident with the gravitational lens 1938+66.6 (Patnaik et al. 1992) in K' ($2.12\,\mu$m), H ($1.6\,\mu$m), J ($1.25\,\mu$m), and Thuan-Gunn r ($0.65\,\mu$m) bands. 1938+66.6 has previously been detected as a partial radio ring indicating lensing. We find $K' = 17.1 \pm 0.1$ and $r = 23.9 \pm 0.2$, making it a very red source with $(r - K') = 6.8 \pm 0.25$. We also observed in Thuan-Gunn g band ($0.49\,\mu$m) and found $g > 24.5$ at the 90% confidence level. We interpret our observations as a reddened gravitational lens on the basis of its optical-IR color and positional coincidence with the radio source.

1.   Introduction

There is increasing evidence that quasars and gravitationally lensed quasars sometimes have very red optical-infrared colors. Reddening by intervening dust offers an explanation for this phenomenon (Webster et al. 1995, Lawrence et al. 1995, Larkin et al. 1994). Such large reddenings raise questions about possible incompleteness of optical quasar and lens surveys. This in turn can have important implications for cosmological models, since many constraints on cosmological parameters are derived from the luminosity functions of quasars and from the numbers and seperations of lensed quasars (Turner, Ostriker & Gott 84, Fukugita and Peebles 1993, Fukugita & Turner 1991, Malhotra & Turner 1995, Kochanek 1993, Maoz & Rix 1993). The reddening of gravitationally lensed quasars is also a potential probe of the ISM of the lensing galaxies at high redshift.

One would expect the radio selected gravitational lenses to be free of bias against reddened lenses. Also small seperation lenses, where the optical paths are likely to pass near the center of a single lensing galaxy, are more likely to show substantial amount of reddening.

The radio source 1938+66.6 is one of the small seperation gravitational lenses discovered in the VLA/MERLIN survey of flat spectrum radio sources (Patnaik et al 1992).

It has four compact sources and an arc; the maximum seperation between the any of the components is $0''.95$. Patnaik et al report a r=23 object at the location of the lens. We observed this source in the near infrared K' ($2.12\,\mu$m), H ($1.6\,\mu$m), and J ($1.25\,\mu$m) bands, and in the optical Thuan-Gunn r ($0.65\,\mu$m) and g ($0.49\,\mu$m) bands. An object was detected at the position of the lens in all bands except g. This optical-infrared object will hereafter be referred to as "1938+666(OIR)"; we will argue that it is a counterpart of the radio system.

The observations and data analysis are described in section 2. In section 3 we estimate the probability of the infrared source being a cool star or a high redshift galaxy on the basis of color. Discussion and posssible interpretation of the results are presented in section 4.

2.   Observations

We observed 1938+666 in H band on 2 July 1995 (UT), in J and K' bands on 6 August 1995 (UT), and in Thuan-Gunn g and r bands on 4 and 24 July and 5 August 1995 (UT). There was intermittent scattered cloud cover early on the night of 2 July, but the sky cleared shortly before the 1938+666 H band observations. All data were taken with the Apache Point Observatory[1] 3.5 meter telescope. The near-IR observations used the GRIM II camera, while the g and r band observations used the Double Imaging Spectrograph (DIS) in imaging mode. Seeing was about $1.6''$–$1.8''$ FWHM in all bands. Some parameters of the observations are summarized in table 1.

All data reduction was done using the IRAF package and followed standard procedures. For the near-IR data, individual short exposures were sky subtracted, typically using the 2–4 sky frames nearest in time. A sky flat was made by taking the median of all disregistered exposures in a band, subtracting a mean bias frame, and normalizing the result by its median pixel value. The sky subtracted image frames were then divided by this flat. Finally, the images were registered (using the centroid of a bright star to determine fractional pixel shifts) and a combined image was produced by taking the median of all processed single frames at each pixel. For the g and r bands processing was similar but no sky subtraction step was needed. Final images are shown in figure 1.

On the nights 2 July, 4 July, and 6 August we also observed photometric standards to calibrate our fluxes. For the H band, we used the UKIRT faint standard FS 28; for J and

---

[1]APO is privately owned and operated by the Astrophysical Research Consortium (ARC), consisting of the University of Chicago, Institute for Advanced Study, Johns Hopkins University, New Mexico State University, Princeton University, University of Washington, and Washington State University.

K' bands we used FS 7 (Casali & Hawarden 1992). For the g and r bands, we used the fields Mark A (Jorgensen 1994, Landolt 1992) and F1038-6 (Jorgensen 1994, Stobie et al 1985).

2.1. Data Analysis

We determined the position of the radio source using three HST guide stars that fell within the r band image (epoch 2000.0 coordinates 19 38 14.23 +66 50 23.99, 19 38 45.36 66 48 40.38, and 19 38 01.38 +66 51 14.11). We first used the guide stars to determine the position and orientation of the coordinate grid, and then determined the position of the quasar relative to each guide star. The scatter in the resulting position estimates was $0.7''$ in RA and $0.4''$ in declination.

In the r, J, H, & K' bands, the counterpart to 1938+666 is apparent, and we have done conventional aperture photometry to measure its fluxes. In the g and r bands we have applied additional tests to see if an object is detected and to place upper limits on the counterpart flux. Our results are reported in Table 1.

We measured aperture magnitudes with radii $\sim 0.67a$ where a is the FWHM (full width at half maximum) of the psf (point spread function) and the coefficient 0.67 maximizes the signal to noise for aperture photometry of a faint source with a Gaussian psf.

To see if the resulting g and r fluxes are significantly above background, we measure fluxes in randomly placed apertures and determine how frequently the flux exceeds that seen for 1938+666. The result is not very sensitive to aperture size for $1.5'' \lesssim a \lesssim 2.0''$. In g band, 89% of randomly placed $1.5''$ apertures had fluxes exceeding that for 1938+666, and we conclude there is no evidence of a g band counterpart to the radio source. In r band, 18% of randomly placed $1.5''$ apertures had fluxes exceeding that for 1938+666. Visual inspection of the final r band image shows a source at the location of the NIR source, and we believe that the weak result of the random aperture test is due to bleeding columns from saturated bright stars and to the substantial density of 23rd magnitude objects on the sky.

By modelling the counts in an aperture of area A pixels as the object flux plus sky noise, we may place an upper limit on the total flux for a point source (modelled as a Gaussian psf) at the H band source location. At confidence levels of (90%, 99%, and 99.9%) we find $g > (24.5, 24.0,$ and $23.7)$ mag. Applying the same formalism to the weakly detected r band source gives $r > (23.75, 23.6,$ and $23.5)$ mag.

A source substantially larger than the psf could be brighter than the total magnitude limits quoted above. Additionally, the spectral slope of the putative candidate will influence

the r band limit, since our standard star observations suggested a substantial color term $(-0.15(g - r))$ in the transformation from instrumental to standard r magnitude. No important color term was apparent in g band. We were not able to observe enough NIR standards to allow secure color term corrections in J, H, and K' bands.

3. Interpretation

To test the interpretation of 1938+666(OIR) as the counterpart of the radio source 1938+666, we compared its measured colors to those of galactic stars, normal galaxies, quasars, and lensed systems. We first account for Galactic foreground dust. Reddening towards 1938+666 can be estimated at $0.10 \leq E(B - V) \leq 0.12\,\mathrm{mag}$, based on the reddening map of Burstein & Heiles (1982). The normal galactic extinction law (with $R_V \equiv A(V)/E(B - V) = 3.1$) yields $E(r - K) \approx 2.25E(B - V)$ (cf. Mathis 1990). Thus, Galactic dust does not contribute strongly to the extremely red color of 1938+666(OIR).

Our data indicate $(r - H) = 6.3 \pm 0.25\,\mathrm{mag}$, $(r - K') = 6.8 \pm 0.25\,\mathrm{mag}$, $(J - H) = 2.1$, and $(H - K') = 0.5$.

For comparison, data in Bessell (1991) plus the color transformations of Jorgensen (1994) give $(r - H) \approx 6$ for the M6.5 dwarf LHS 3003, and $(r - H) \approx 6.8$ for an M7.5 dwarf. Thus, only the very coolest stars have colors as red as 1938+666.

Two further tests may be applied to the hypothesis that the object is a very cool star. First, we can see if 1938+666(OIR) is appreciably broader than a point source. In the present H band data, the FWHM of 1938+666(OIR) is $\sim 2.4''$, while a representative stellar FWHM is $\sim 1.8''$. This would be consistent with a source of size $\sim 1''$, but better seeing and a larger signal to noise ratio are required before this test can be considered conclusive. Second, we can use Wainscoat et al's (1992) model of the near-IR sky to calculate the number density of "M late V" dwarfs with $18 < H < 19$ towards 1938+666; the resulting density is $0.25/\mathrm{arcmin}^2$, giving a probability $\sim 2 \times 10^{-3}$ of finding a suitably red M dwarf within 3 arcseconds of the radio source.

We can also compare the observed color limit to the colors of normal galaxies. The reddest local elliptical galaxies have $(r - H)$ colors around 2.75 (Persson, Frogel, & Aaronson 1979), while moderate redshift ellipticals (z up to 0.92) show $(r - H) \leq 4$ (Persson 1988). By redshift $z \approx 1.2$, elliptical galaxies can have $R - K$ up to 6 (Dickinson 1995), and the central component of the $z = 2.016$ radio galaxy 0156−252 has $r - K = 7.3$ (McCarthy, Persson, & West 1992), so the color of 1938+666(OIR) is consistent with a lensing galaxy or a lensed radio galaxy at $z > 1$. Spiral galaxy $(r - H)$ colors are not widely published,

but an examination of de Jong's work suggests that $2.5 \lesssim (r-H) \lesssim 3$ is typical while occasional exceptions (e.g. UGC 4256) might be a magnitude redder. (de Jong, 1995).

Taken together, the close positional coincidence and unusually red color are strong circumstantial evidence that 1938+666(OIR) is indeed the gravitational lens system observed in the radio by Patnaik et al. (1992). This interpretation might be confirmed by obtaining an image in sub-arcsecond seeing and comparing the near-IR and radio morphologies; or (preferably) by obtaining a spectrum, and measuring a redshift if the object is indeed a quasar. Either of these tests might determine if the observed infrared source is the lensed object or a high redshift lensing galaxy.

The optical-IR colors of many lensed quasars are found to be as red or redder than observed for 1938+666(OIR) (Lawrence et al. 1994, Larkin et al. 1994, Annis & Luppino 1993, Annis 1992). The most extreme red colors are seen for MG 0414+0534: $(r-H) = 7.8$, and for MG1131 +0456: $(J-K) > 4.1$. To compare the reddening directly one needs the redshift of the lens and the dust responsible for the reddening. Optical-IR colors of radio selected quasars can also be quite red. Webster et al. 1995 report $B_J - K \approx 2-7$ for the confirmed quasars among the flat-spectrum radio sources observed with the Parkes telescope, and up to $B_J - K \approx 8$ for the sources for whom the redshift is not known. The red color of 1938+666(OIR) support its identification as a counterpart to the gravitationally lensed radio ring.

4.   Conclusions

We have detected an infrared object at the location of the radio-detected gravitational lens 1938+666, with very red colors ($r - K' = 6.7\,\mathrm{mag}$). The most natural explanation for these observations is that the we are seeing the lensed object or a lensing galaxy at large redshift ($z \gtrsim 1$). The close positional coincidence observed is quite unlikely to happen for random field stars or galaxies, with the exception of the lensing galaxy. Moreover, empirical measurements show that $r - K'$ colors of most stars and low to moderate redshift field galaxies are bluer than our observed limit. On the other hand, a moderate fraction of flat-spectrum radio sources and gravitationally lensed quasars are similarly red. Our interpretation could be tested by imaging 1938+666 with higher spatial resolution, or taking a spectrum of this object.

REFERENCES

Annis, J. 1992, ApJ 391, 17

Annis, J. & Luppino, G. A. 1993, ApJ 407, 69

Bessell, M. S. 1991, AJ 101, 662

Burstein, D., & Heiles, C. 1982, AJ 87, 1165

Casali, M. & Hawarden, T. 1992, JCMT-UKIRT Newsletter 4, 33

de Jong, R. S. 1995, thesis

Dickinson, M. 1995, in "Fresh Views on Elliptical Galaxies"

Fukugita, M., & Peebles, P. J. E. 1993, Institute for Advanced Study preprint number IASSNS-AST 93/24

Fukugita, M., & Turner, E. L. 1991, MNRAS 253, 99.

Jorgensen, I. 1994, PASP 106, 967

Kochanek, C. S. 1993, ApJ 419, 12

Landolt 1992, AJ 104, 340

Larkin, J. E.; Matthews, K.; Lawrence, C. R.; Graham, J. R.; Harrison, W.; Jernigan, G.; Lin, S.; Nelson, J.; Neugebauer, G.; Smith, G 1994 ApJ, 420, l9.

Lawrence, C.R., Elston, R., Januzzi, B.T., Turner, E.L. 1995, preprint

Malhotra, S. & Turner, E. L. 1995, ApJ 445, 552

Maoz, D., Rix, H-W, 1993, ApJ 416, 425

Mathis, J. S. 1990, ARA&A 28, 37

McCarthy, P. J., Persson, S. E., & West, S. C. 1992, ApJ, 386, 52

Patnaik, A., Browne, I., King, L., Muxlow, T., Walsh, D., & Wilkinson, P. 1993, in "Sub-Arcsecond Radio Astronomy," edited by R. Booth & R. J. Davis (Cambridge: Cambridge University Press), 137

Persson, S. E., Frogel, J. A., & Aaronson, M. 1979, ApJS 39, 61

Persson, S. E. 1988, in "Towards Understanding Galaxies at Large Redshifts," eds. R.G. Kron & A. Renzini, 251

Stobie, R. S. et al 1985, A&A Supp, 60, 503

Turner, E. L., Ostriker, J. P., & Gott, J. R. 1984, ApJ 284, 1

Wainscoat, R. J. et al, 1992 ApJS 83, 111

Webster, R.L., Francis, P.J., Peterson, B.A., Drinkwater, M.J., Mascl, F.J. 1995, Nature, 375, 469

Fig. 1.— Images of the 1938+666 field in all 5 bands: first row, K' and H; second row, J and r; third row, g and H (this time with 1938+666(OIR) indicated by a cross). Each image is 90 arcseconds on a side. North is up, East is to the left.

Table 1: Characteristics of the observations.

Filter	central wave-length (μm)	bandpass FWHM (μm)	On source integration time	Individual exposure time	Magnitude
K'	2.12	0.35	12.3 min	9 s	17.1 ± 0.1
H	1.65	0.30	20 min	25 s	17.6 ± 0.1
J	1.25	0.30	12.1 min	25 s	$19.7 \pm .13$
r	0.655	0.09	48 min	3, 5 min	23.9 ± 0.22
g	0.493	0.07	48 min	3, 5 min	$> 24.3(95\%)$